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Applicability Study on a Hybrid Renewable Energy System for Net-Zero Energy House in Shanghai

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Abstract

Governments around the world are establishing technological routes and tactics for low/zero-energy buildings to reduce emissions and energy use. This paper describes a hybrid renewable energy system developed for a net-zero energy low-rise residential building located in Shanghai, China. This hybrid renewable energy system consists of a water-based photovoltaic/thermal (PVT) collector and a ground water-source heat pump (GWSHP). The hybrid system is designed to produce heating, cooling and electricity during both winter and summer by using solar energy and ground surface water energy respectively. Firstly, field tests on the PVT collector and GWSHP were carried out to obtain their thermal performance, and then analytical models for the PVT collector and performance curve of the GWSHP were developed and validated by the experimental data. In addition, the balance between annual energy production and consumption was estimated to evaluate the applicability of this system for the on-grid net-zero energy residential building in Shanghai. It is shown that the detached house with the PVT-GWSHP system can provide 109.3% of total requirements for heating, cooling and electricity, and has potentials to realize the net-zero energy target.

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Keywords: Net-zero energy building; Photovoltaic/thermal collector; Ground water-source heat pump; Building energy simulation.

1. Introduction

The utilization of renewable energy for low/zero-energy buildings mainly includes solar photovoltaic technology, solar thermal technology, ground source heat pump and etc. [1]. Photovoltaic/thermal (PVT)

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collector is an efficient holistic solar energy solution that simultaneously converts solar energy into electricity and heat [2]. A trend of comprehensive utilization of renewable energy and low-level thermal energy is to integrate the PV system with the heating, ventilation, and air conditioning (HVAC) system. Up to date, various studies have been undertaken on solar heating system [3], solar-absorption refrigerating system, solar assisted ground source heat pump heating system [4], etc. However, the promotion and application of these hybrid renewable energy systems, sustainable operation has become the major constraints. The energy supply of solar photovoltaic/thermal system is unstable due to the influence of weather variations, and the performance of ground source heat pump is limited by site condition and source capacity. Therefore, the maximum utilization of those renewable system has not been well studied.

This study developed and implemented an innovative HVAC system incorporating a hybrid renewable energy system, sufficiently utilizing solar energy to generate electricity as well as to pre-heat the water into the GWSHP. The heated water then improves the secondary heating efficiency of GWSHP in winter and reduces the domestic hot water heating energy through the year. The objective of this study is to prove the applicability of this hybrid renewable energy system particularly for zero-energy house in Shanghai, the hot-summer and cold-winter zone of China with insufficient solar irradiation.

2. System introduction

2.1. Building and system layout

The experimental house as shown in Figure 1 locates in Shanghai, China. The specification is shown in Table 1. The PVT collectors are implemented on the roof within the building's footprint. The electricity generated by the PVT can access city power grid after converted into alternating current by the inverter. The PVT collector heats water coming from the water storage tank and thereby provides heating to the heat storage water tank connected with the ground heat exchanger as the hot water source in winter. Ground surface water piping system is also implemented as an alternative water source to the heat exchanger, which is illustrated in Figure 2.

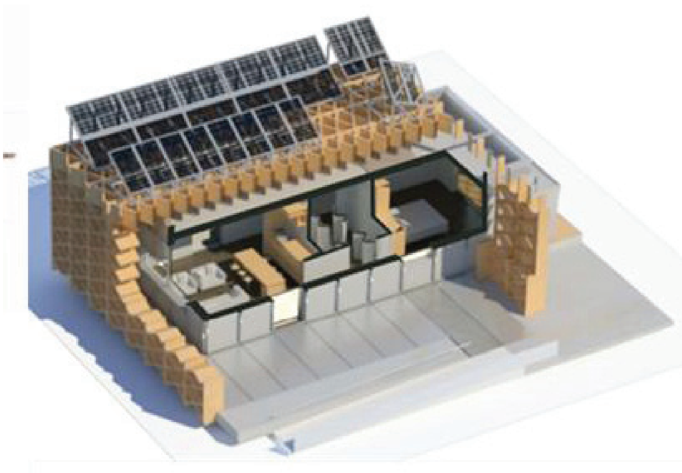


Figure 1 Zero-energy residential house

Table 1. Residential building specification

Items	Value
Floor to ceiling height	3.05 m
HVAC system	Fan coil; Temperature & humidity independently controlled
Ventilation rate	30 m^3/h person
Hot water	200 L/day
Building envelope	
Exterior walls	0.1 W/(m^2.K)
Interior walls	0.4 W/(m^2.K)
Windows	0.8 W/(m^2.K); Solar heat gain coefficient (SHGC) 0.5
Glass door	0.8 W/(m^2.K); Solar heat gain coefficient (SHGC) 0.5
Roof	0.12 W/(m^2.K)
Shading coefficient (SC)	0.73

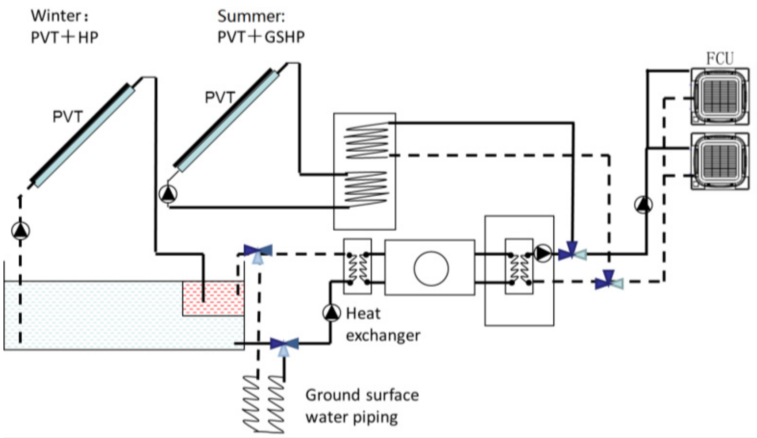


Figure 2 Schematic of system configurations: GWSHP and PVT

2.2. Operating strategies

In winter, since the daily solar radiation is unsteady, when the temperature of the heat storage water tank goes below the lower limit, the ground heat exchanger will switch the valves to the ground surface water piping system as water source. The temperature of the hot water storage tank and water storage tank would be kept in a proper range, to meet both the demand of the heat pump and PVT module.

During the cooling season, the valves are switched to ground surface water piping system, providing cooling water for the heat exchanger and the return water goes to the water storage tank. Domestic hot water can be made by the heat pump when valves are switched to the hot water storage tank.

3. System test and modelling

3.1. Field test parameters

Field test had been conducted through the year. Parameters including inlet/outlet temperature, flow rate, electricity production/consumption, solar radiation intensity, COP of GWSHP and generating capacity and efficiency of PVT were recorded.

3.2. PVT analytical model

By synthesizing and test data analysis, the soar irradiation intensity, PVT inlet water temperature and ambient temperature appear as three specific parameters of PVT heat-collecting efficiency. Then mathematical model can be established by regressing fitting, with difference less than 15%. Similarly, the PV panel temperature and irradiation intensity are specific parameters of PVT generating efficiency, but those two parameters are not mutual independent, a large portion of solar irritation will convert to heat, thus raise the temperature of PV panel. A practical method is discovered that divides the date with specific temperature range, the generating efficiency and thermal collecting efficiency of the PVT can be obtained with a good consistency (as shown in Figure 3 and 4) by regression analysis which has linear performance with incident solar irradiation. The summary of the PVT mathematical model is given in Table 2.

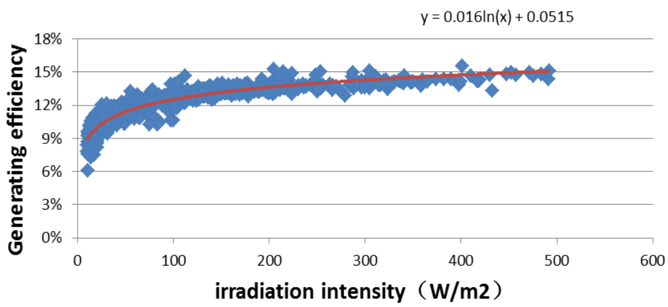


Figure 3 PVT generating efficiency

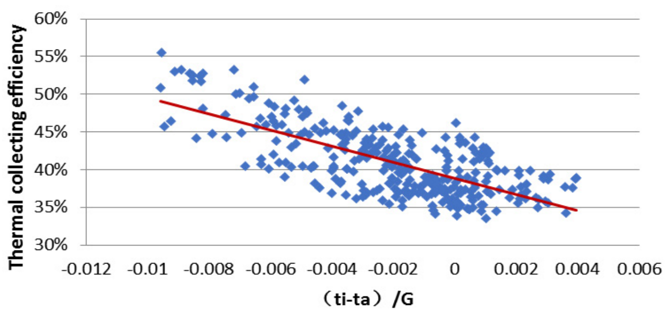


Figure 4 PVT thermal collecting efficiency

Table 2 Summary of the PVT mathematical model

Conditions	Equation
5~25°C, 0~1000W/m²	$\eta_{pv} = 0.0161 InG + 0.515$
25~35°C, 0~500W/m²	$\eta_{pv} = 0.0161 InG + 0.515$
25~35°C, 500~1000W/m²	$\eta_{pv} = 0.11993 - 9.3 \times 10^{-6} G$
35~60°C, 0~1000W/m²	$\eta_{pv} = 0.15028 - 3.88 \times 10^{-5} G$
5~60°C, 0~1000W/m²	$\eta_{th} = 0.3844 - 10.692(\frac{t_i - t_a}{G})$

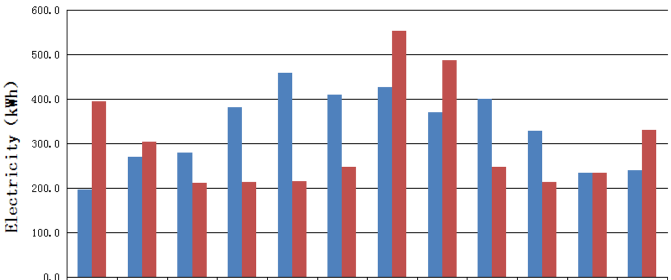
4. Results and discussion

4.1. Annual energy consumption/production

The annual energy consumption of the studied system was 3658.7kWh, and the overall energy consumption intensity was 65.3kWh/m^2. The breakdown demonstrated that HVAC annual consumption was 2076.0kWh, lighting was 648.7Wh, and the rest were other equipment consisting of 934.1kWh.

The installed capacity of PVT collector is 26.2m^2, and the volume of the hot water storage tank is 1.4m^3. The annual energy production can be calculated by the PVT mathematical model using the Solar and Wind Energy Resource Assessment (SWERA) data of Shanghai. Figure 5 shows the monthly power generation and consumption of the building. The annual on-site power generation intensity was 152.6kWh/ m^2.

The annual energy consumption and production for the whole year is illustrated in Figure 6. During the heating period, the total electricity generation is 1222.7 kWh, thermal energy collection is 2122.0 kWh, while the system energy consumption is 1476.7 kWh. While during the cooling period, the total electricity generation is 1608.5 kWh, thermal energy collection is 4517.1 kWh, while the system energy consumption is 1538.0 kWh. Besides, the low-level thermal energy is utilized through the year. During the cooling and transition seasons, the PVT heated water is not consumed by the HVAC system, however this accordingly contributes to reduce the energy consumption of domestic hot water supply.



	1	2	3	4	5	6	7	8	9	10	11	12
Gen	197.5	269.9	280.2	381.4	459.3	410.3	426.4	370.8	400.8	328.4	235.3	239.7
Con	394.7	304.0	212.7	214.0	216.2	248.4	553.5	487.6	248.5	213.9	234.1	331.2

Figure 5 Annual power generation/consumption

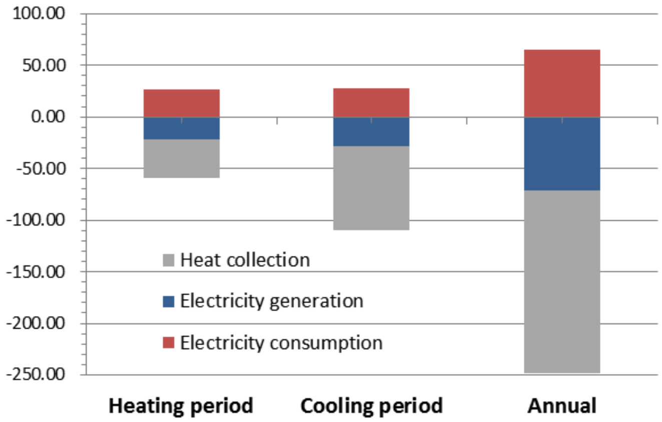


Figure 8 Annual energy consumption and production

5. Conclusions

This paper introduced an innovative hybrid PVT-GWSHP renewable energy system for a net-zero energy house, which is designed to produce heating, cooling and electricity during both winter and summer by using solar energy and ground surface water energy respectively. The applicability of the hybrid PVT-GWSHP system in detached house located in hot summer and cold winter city Shanghai was evaluated by both field test and modelling analysis. The annual energy consumption of the studied case is 3658.7kWh, less than the annual on-site energy generation 4000.1kWh, and the system has been proved to be applicable on this on-grid zero-energy house, and hence has potential for low/zero-energy low-rise residential buildings in Shanghai. The utilization of the test and simulation data for system optimization, as well as the economic analysis and environment impact assessment for the system will be studied in near future.

Acknowledgements

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Nomenclature

η_{pv}	Generating efficiency of PVT
η_{th}	thermal collecting efficiency of PVT
G	Irradiation intensity
t_i	Inlet water temperature
t_a	Ambient temperature

Biography

Dr. Zhi Zhuang is an Assistant Professor from the College of Architecture of Urban Planning in Tongji University of China. His research interest is building energy efficiency, renewable energy application and green building design.